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LIGHT LOAD EFFICIENCY IMPROVEMENTS IN DUAL FUEL ENGINES BY MEANS OF THROTTLING AND EXHAUST GAS RECIRCULATION

TE-87-7

DISCLAIMER

This study was carried out with the cooperation of the Department of Energy, Mines and Resources. However, the views expressed in the report are those of the author and do not necessarily reflect the views of the Department.

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ABSTRACT

A naturally aspirated Caterpillar 3208 diesel engine has been operated on dual fuel (diesel/natural) gas and diesel fuel. Light load efficiency improvements were attempted using throttling and exhaust gas recirculation. At loads of less than 50% throttling produced efficiency improvements of about 10%, and allowed less pilot fuel to be used for comparable efficiency. Throttling also caused a 70% increase in exhaust temperature. Exhaust gas recirculation had a smaller effect on efficiency, probably due to the oxygen content of the exhaust.

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1.0 INTRODUCTION

Natural gas fuelled diesel engines suffer from low light load efficiency compared to their pure diesel counterparts [1,2,3]. Earlier work done at BC Research showed that dual fuel engines are up to 40% less efficient at light load, compared to diesel only operation. In some operating conditions, this lack of efficiency negates the cost difference of the two fuels.

In the past, experiments have been done on single cylinder diesel engines to investigate efficiency improvements. For the most part this work has been done at low speed, and little attention has been paid to multi cylinder engines.

Previous work [1,4,5] has shown that this loss in efficiency is caused by lean gas-air ratios. In this report the gas-air equivalence ratio is calculated assuming all diesel fuel has been burnt [1]. Figure 1 shows brake thermal efficiency vs equivalence ratio for a dual fuel conversion system developed at BC Research operating on a Caterpillar 3208 engine. The dependence of efficiency on airfuel ratio seems to be quite strong.

Several methods can be used to enrich the fuel air mixture at light loads, including charge preheat, throttling and use of an inert diluent. Charge preheat decreases the density of the charge by increasing its temperature, Throttling reduces the amount of air admitted to the engine, and an inert diluent reduces the amount of oxygen available in the charge.

The difficulty with charge preheating is that a reasonable increase in efficiency requires the inlet temperature to be raised to 250 C [6], which is higher than the exhaust temperature of the engine at light loads, therefore an external source is required to heat the intake air.

Thermal Efficiency vs Equivalence Ratio

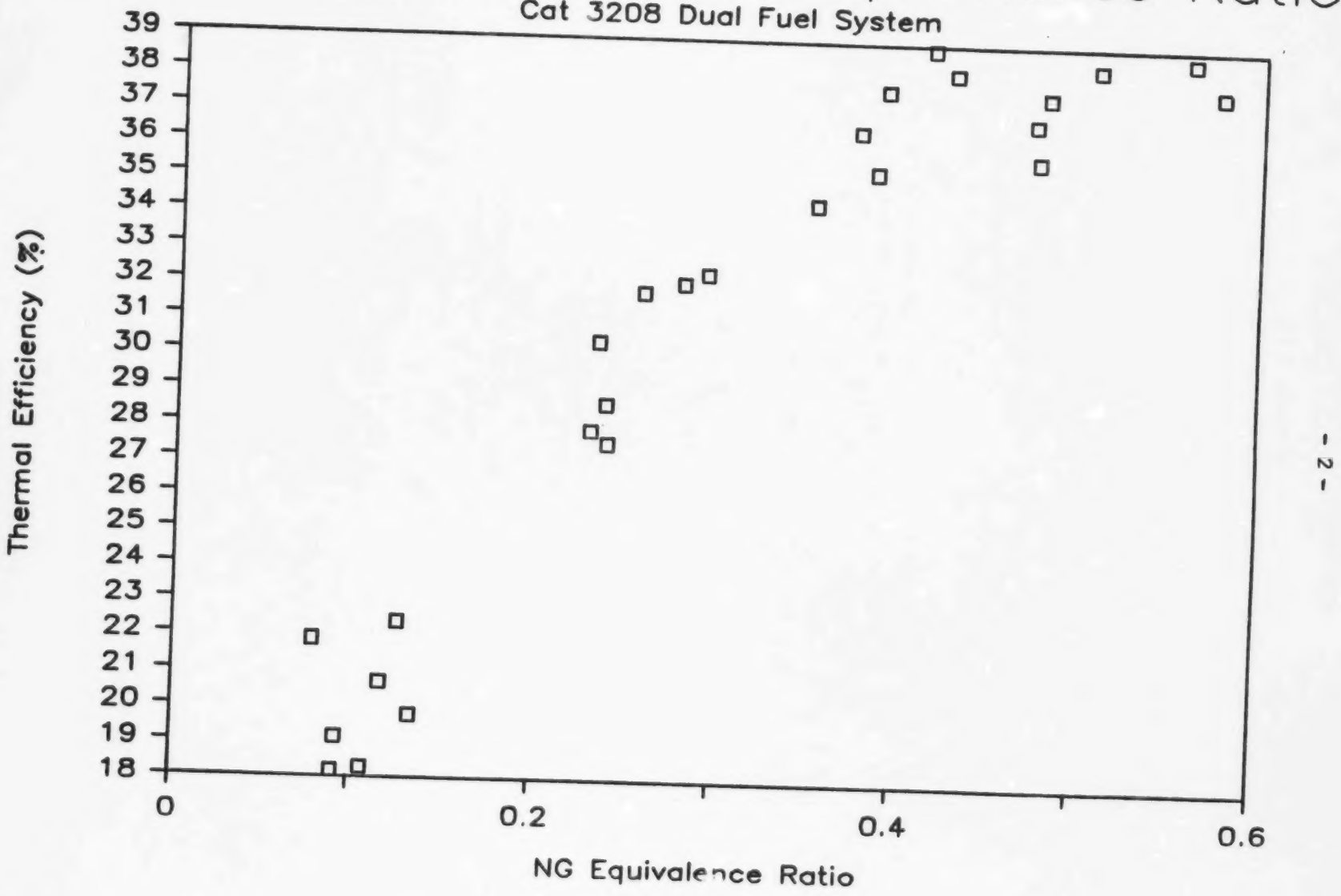


FIGURE 1

Throttling does not involve major engine modifications. Referring to Figure 1, brake thermal efficiency reaches a maximum at fuel air ratios above 0.4. Assuming comparable efficiency at light load, the intake air needs to be throttled about 40% to produce a fuel air ratio of 0.4. There will be some reduction in efficiency due to throttling losses.

To reduce throttling losses and still reduce the amount of oxygen in the charge (hence a richer mixture) an inert dilution gas can be introduced into the inlet air. This dilution gas could be an inert gas such as carbon dioxide or nitrogen, or it could be exhaust gas. Exhaust gas recirculation (EGR), or the use of inert gases have been studied in connection with emissions reduction in diesel engines [7], but EGR has never been used as a diluent in dual fuel engines, or as a method of enriching fuel air mixtures without the penalties of throttling.

This report describes a series of experiments on improving the part load efficiency of a dual fuel Caterpillar 3208 engine by throttling and EGR.

2.0 TEST METHODOLOGY

2.1 Test Engine

The experiments were carried out on a Caterpillar 3208 diesel engine. This is a naturally aspirated direct injection V8 engine with a displacement of 10.4 litres. The fuel system was modified for the tests as described below. Engine specifications are shown in Table 1.

Table I

Caterpillar 3208 Engine Specifications

Type	Diesel
Aspiration	Naturally Aspirated
No of Cylinders	8 Vee
Bore	114.0 mm (4.5 in)
Stroke	127.0 mm (5.0 in)
Displacement	10.4 l (636 in^3)
Power	157 kW (210 HP)
Rated Engine Speed	2800 rpm
Governed Engine Speed Range	650-3030 rpm

2.2 Fuel System

BC Research has developed a microprocessor control system for the 3208 Caterpillar engine. The system uses a stepping motor in the fuel pump to control the amount of diesel fuel, and a stepping motor controlled valve in the natural gas line. Separate controls for the stepping motors were fitted, allowing independent adjustment of each fuel to allow a wide range of diesel/gas combinations to be explored.

Diesel fuel was supplied to the engine through the modified diesel fuel pump. Natural gas was supplied to the engine by feeding the gas into the intake tract upstream of the throttle assembly (see below). Gas flow was controlled by a stepping motor controlled valve supplied by a 65 kPa regulated supply.

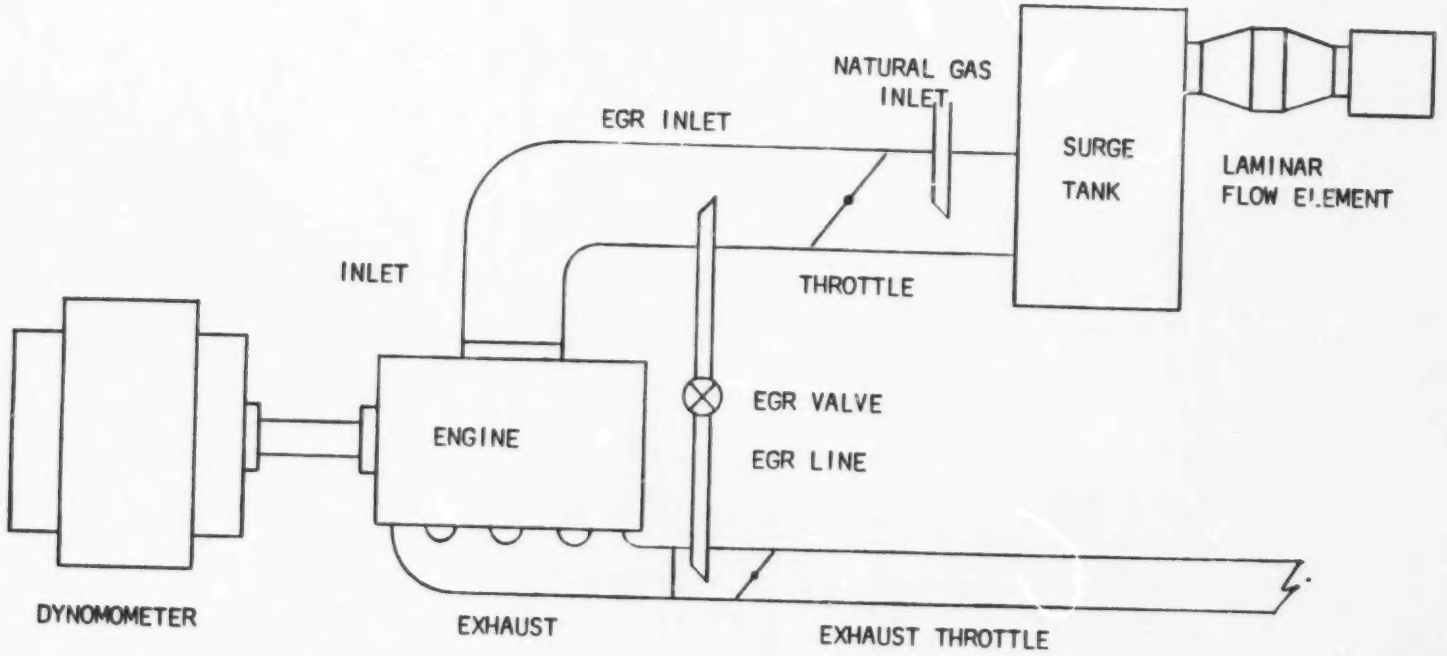
Fuel measurement was done using Micro Motion mass flow meters. Natural gas was metered at storage pressure before the regulators that supplied the engine, while diesel fuel was measured at the supply to the float tank, so that fuel recirculation, de-aeration, and cooling were downstream of the flowmeter.

2.3 Throttling and Exhaust Gas Recirculation

A throttle was installed in the air inlet tract about 60 cm upstream of the inlet manifold. The throttle could be adjusted manually, and be locked in place for testing. An absolute pressure sensor was placed downstream of the throttle for measuring manifold pressure. Intake air flow was measured by a laminar flow element mounted at the inlet to a surge tank upstream of the throttle.

EGR was done by connecting a line from the exhaust system to the inlet tract. A throttle was installed in the exhaust to raise the back pressure to provide sufficient exhaust flow and a valve was placed in the exhaust line to regulate the quantity of exhaust admitted to the air inlet. The amount of EGR was determined by measuring the change in inlet air flow quantity. A pressure sensor was mounted in the exhaust system to measure exhaust back pressure.

Figure 2 is a diagram of the throttling and EGR system.



EGR AND THROTTLING SYSTEM

FIGURE 2

2.4 Dynamometer and Controls

The engine was installed in the BC Research dynamometer cell. The dynamometer is an Eaton Dynamatic eddy current dynamometer of 700 hp capacity, controlled by a Digalog dynamometer controller which controls either speed or load. The dynamometer controller is controlled by the data acquisition system, while the engine was controlled by a remote throttle actuator. Engine cooling was done with a cooling column.

2.5 Instrumentation

Quantities measured in the test program included engine speed, load, fuel consumption, intake airflow and temperature, exhaust gas temperatures at each exhaust port, pressures in the inlet and exhaust system, ambient air temperature, pressure and humidity,fuel, oil, and coolant temperatures.

Engine speed and load are measured using a toothed-wheel and magnetic pickup, and a strain gauge load cell on the dynamometer. Intake air flow was measured with a laminar flow element, while manifold pressure was measured with a strain gauge absolute pressure transducer. Exhaust temperatures were measured at each exhaust port with K type thermocouple probes. Fuel consumption was measured with Micro Motion flowmeters as described above. All other pressures were measured with strain gage pressure transducers.

2.6 Data Acquisition

Data acquisition was done with an IBM PC with a Scientific Solutions data acquisition system. The system enables an IBM PC to control the dynamometer and (for this test program) record all data from the instrumentation described above. Output from the data acquisition system is put into Lotus 1-2-3 spreadsheet files for reduction.

3.0 TEST PROCEDURE

3.1 Throttling Tests

Throttling tests at light load were carried out at two speeds, 1400 and 2600 rpm, and at four loads, 20 (25% at 2600 rpm), 30, 40,and 50% of full load at each of the two speeds. Previous work has shown that efficiencies at 50% load and above are comparable to efficiencies of pure diesel operation. Calculations showed that reduction of inlet air flow to 60% of its unthrottled value would give fuel air equivalence ratios of about 0.4. The throttling experiments were done at airflow rates of 60,70,80,90, and 100% of the unrestricted airflow.

During testing, engine speed was fixed and airflow was set by running the engine on 100% diesel fuel (to eliminate the displacement of air caused by using natural gas) and closing the throttle until the desired airflow was found, where the throttle was locked in position. Diesel fuel flow was fixed, and gas flow was varied to give the desired load. Two diesel fuel flow rates were used at each speed, 40 and 60 grams/minute at 1400 rpm, and 153 and 170 grams/minute at 2600 rpm. The higher of the diesel fuel flows at each speed corresponds to the flow used by the microprocessor control system, and the lower flow corresponds to about 10% greater than the minimum amount of diesel fuel required for smooth dual fuel operation at that speed.

Fuel flow data, showing amounts of diesel fuel used, and diesel pilot level where pilot level is the percentage of diesel fuel required to give the same load with dual-fuel as when operating with 100% diesel, are shown in Table II.

Table II

Pilot Levels Used During Tests

Speed (rpm)	1400		2600	
Fuel Flow (g/min)	40	60	153	170
Fuel Flow (mm^3/stroke)	8.4	12.6	17.3	19.2
Load (%)	Diesel Pilot Level (%)			
20 (25 @2600)	39	58	68	77
30	32	48	63	70
40	25	38	54	60
50	22	34	48	53

3.2 Exhaust Gas Recirculation Tests

Exhaust gas recirculation tests at light load were carried out at two speeds, 1400 and 2600 rpm, and at four loads, 20 (25% at 2600 rpm), 30, 40, and 50% of full load at each of the two speeds. EGR was used to reduce inlet air flow by 10%, 20% and 30% at 2600 rpm and by 10% and 40% at 1400 rpm. At 2600 rpm 40% EGR was not used because the combination of restriction from the exhaust throttle at the required exhaust flow, and the amount of exhaust gas recirculated prevented the engine from running at 50% load at 2600 rpm.

During testing, engine speed was fixed and airflow was set by running the engine on 100% diesel fuel to eliminate the displacement of air caused by using natural gas. The exhaust throttle was closed and the airflow into the engine (measured before the exhaust gas inlet) was monitored until the desired flow rate was reached, where the exhaust throttle was locked into position. Diesel fuel flow was fixed, and gas flow was varied to give the desired load. The same diesel fuel flow rates were used as in the throttling experiments, 40 and 60 grams/minute at 1400 rpm, 153 and 170 grams/minute at 2600 rpm.

3.3 Measurement Procedure

When the engine reaches the desired operating point it was allowed to run for approximately two minutes. The data acquisition system was then activated. The system takes data for two minutes. All quantities but fuel flow are measured 28 times, with means and standard deviations calculated, while fuel flows are totalized for the two minute period. Then, data is stored in a file for later reduction.

3.4 Data Reduction

Data reduction included calculation of efficiency, corrected power and fuel consumption to standard conditions. All calculations were done to SAE Standard J1349.

Brake thermal efficiency was calculated based on the heating values of the fuels. Brake thermal efficiency is defined as:

$$e_{th} = \frac{P}{(Q_d * LHV_d + Q_g * LHV_g)}$$

where P is engine power (measured on a dynamometer, hence the term brake thermal efficiency), Q_d and Q_g are the flow rates of diesel fuel and natural gas respectively, and LHV_d and LHV_g are the lower heating values of diesel fuel and natural gas respectively. Based on analysis done at BC Research the lower heating value of diesel fuel was 43.2 mJ/kg and the lower heating value of natural gas was 46.0 mJ/kg.

Throughout this report the term air fuel or equivalence ratio is used. Two types of equivalence ratio are used, total equivalence ratio, and natural gas equivalence ratio. Equivalence ratio is defined as:

$$\phi = \frac{m_f * F_c}{m_a}$$

where mf is mass flow rate of fuel, Fc is stoichiometric air fuel ratio, and ma is the mass flow rate of air going to the engine. From this it can be seen that equivalence ratio of less than 1 is lean, and greater than 1, rich.

Total equivalence ratio is the equivalence ratio of both fuels or:

$$\phi_{tot} = \frac{m_d * F_{cd} + m_g * F_{cg}}{m_a}$$

where m_d is mass flow rate of diesel fuel, F_{cd} is the stoichiometric air fuel ratio for diesel (14.9 in this case), m_a is mass flow rate of natural gas , F_{cg} is the stoichiometric air fuel ratio for natural gas (16.7 in this case), and m_a is the mass flow rate of air.

Natural gas equivalence ratio is the equivalence ratio for natural gas assuming that the air available to burn with natural gas is that left after all of the diesel fuel burns stoichiometrically, or:

$$\phi_{ng} = \frac{m_g * F_{cg}}{m_a - (m_d * f_{cd})}$$

3.5 Discussion of Errors

3.5.1 Thermal Efficiency

As shown above, thermal efficiency is a based on four measured quantities. Fuel flow is measured to ±3%, and speed and torque are each measured to ±1%, suggesting an error of ±5%. Analysis of efficiency data taken at the same operating point shows a standard deviation of ±2.5%. This suggests that repeatability is better than the predicted error.

3.5.2 Equivalence Ratio

Equivalence ratio is based on three measured quantities; two fuel flows and airflow. The laminar flow element used for measuring airflow has an accuracy of ±2%; and as described above the fuel flows are measured to ±3%. this implies that the error in measuring equivalence ratio is typically <5%.

4.0 RESULTS AND DISCUSSION

Numerous tests were performed at the operating points described above. In the interests of brevity, typical data will be shown.

4.1 Throttling Tests

Figure 3 shows the effect on efficiency of throttling the engine at constant speed, and constant pilot fuel. Throttling was done to 60% of original airflow, and at 1400 rpm, at 20 and 30% load, maximum efficiency occurred at 60% throttling while at 50% load

maximum efficiency was reached at 70% throttling. At 2600 rpm [Figure 4] the maximum efficiency is found between 70% and 80% throttling. As the intake air is throttled, the air fuel ratio becomes richer [Figure 5] giving increased efficiency. Diminishing returns occur as the amount of intake air is reduced due to pumping losses across the throttle plate. This effect is more pronounced at 2600 rpm due to greater pumping losses than at 1400 rpm since the pressure drop remains the same (40 kPa), but the airflow is 65% higher.

A second effect of throttling is to reduce the effect of the amount of pilot fuel. As shown in Figure 6, the smaller amount of pilot fuel has lower efficiency in spite of the richer gas air mixture produced. The smaller amount of pilot fuel does not produce enough ignition sources to cause all of the gas to react. However, when the engine is throttled, the pilot fuel effect is eliminated, due to the richer (overall) mixture.

Efficiency vs load data is shown in Figure 7 for the engine operating on diesel and dual fuel at 1400 rpm. Note that even with throttling there is a considerable decrease in efficiency compared to 100% Diesel operation, and that throttling recovers about half the loss in efficiency from diesel to unthrottled dual fuel.

Throttling has some additional side effects. The air fuel mixture is richer when the engine is throttled, and this leads to a significant increase in exhaust gas temperatures [Figure 8]. This temperature increase appears to be independent of pilot fuel quantity, and it should be noted that the temperatures increase as much as 90% compared to unthrottled operation. This can raise the exhaust temperature to above that at at full load on unthrottled diesel.

In conclusion the effects of throttling the dual fuel engine at light load are:

- an increase in thermal efficiency
- for a given thermal efficiency,a decrease in the amount of pilot fuel required for acceptable operation
- as engine speed increases, a decrease in the amount of throttling required for maximum increase in efficiency
- a 90% increase in exhaust gas temperatures.

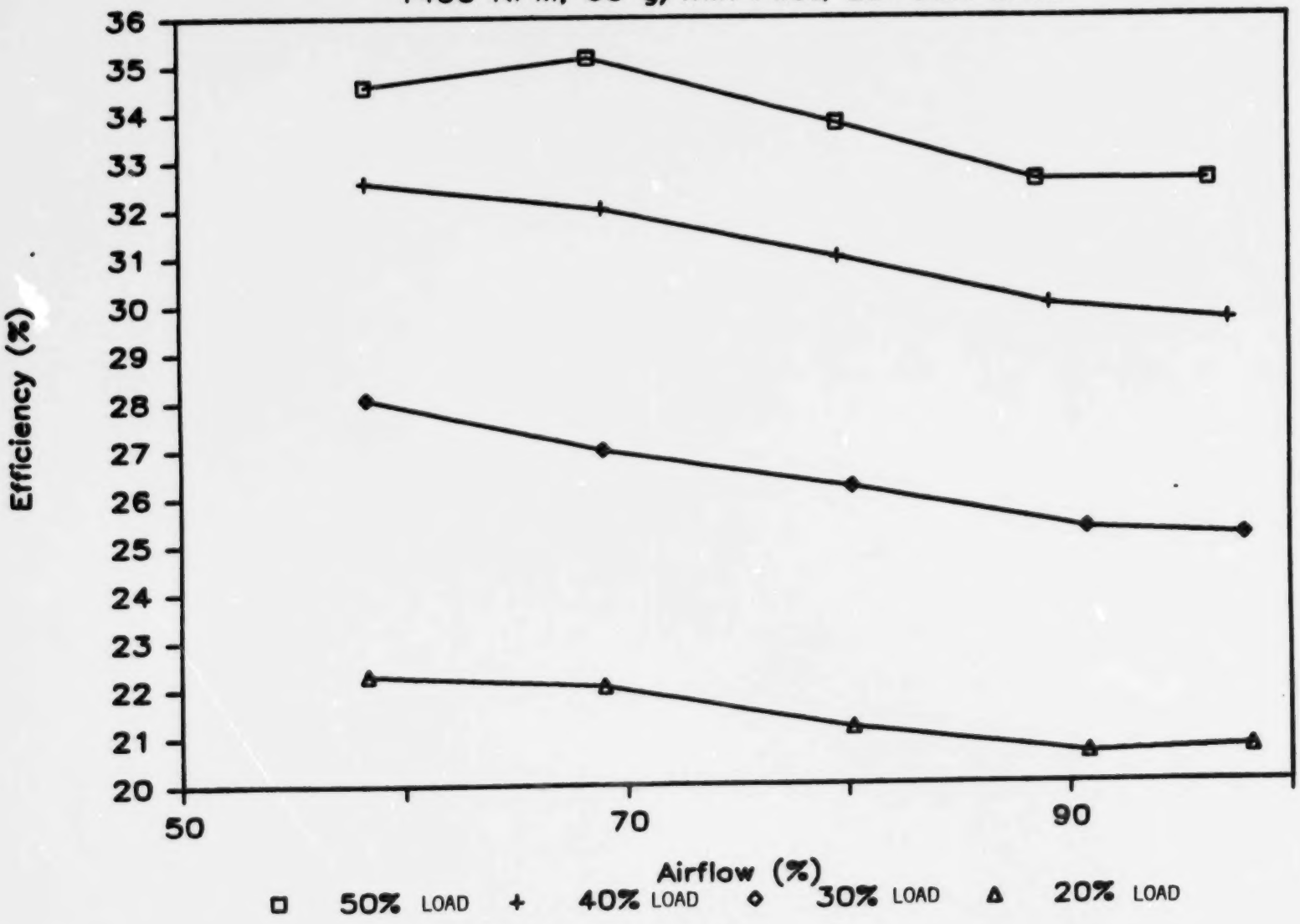

Efficiency vs Airflow
1400 RPM, 60 g/min Pilot, 20–50% Load
Efficiency (%)
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
50
70
90
Airflow (%)
50% LOAD
40% LOAD
30% LOAD
20% LOAD

FIGURE 3

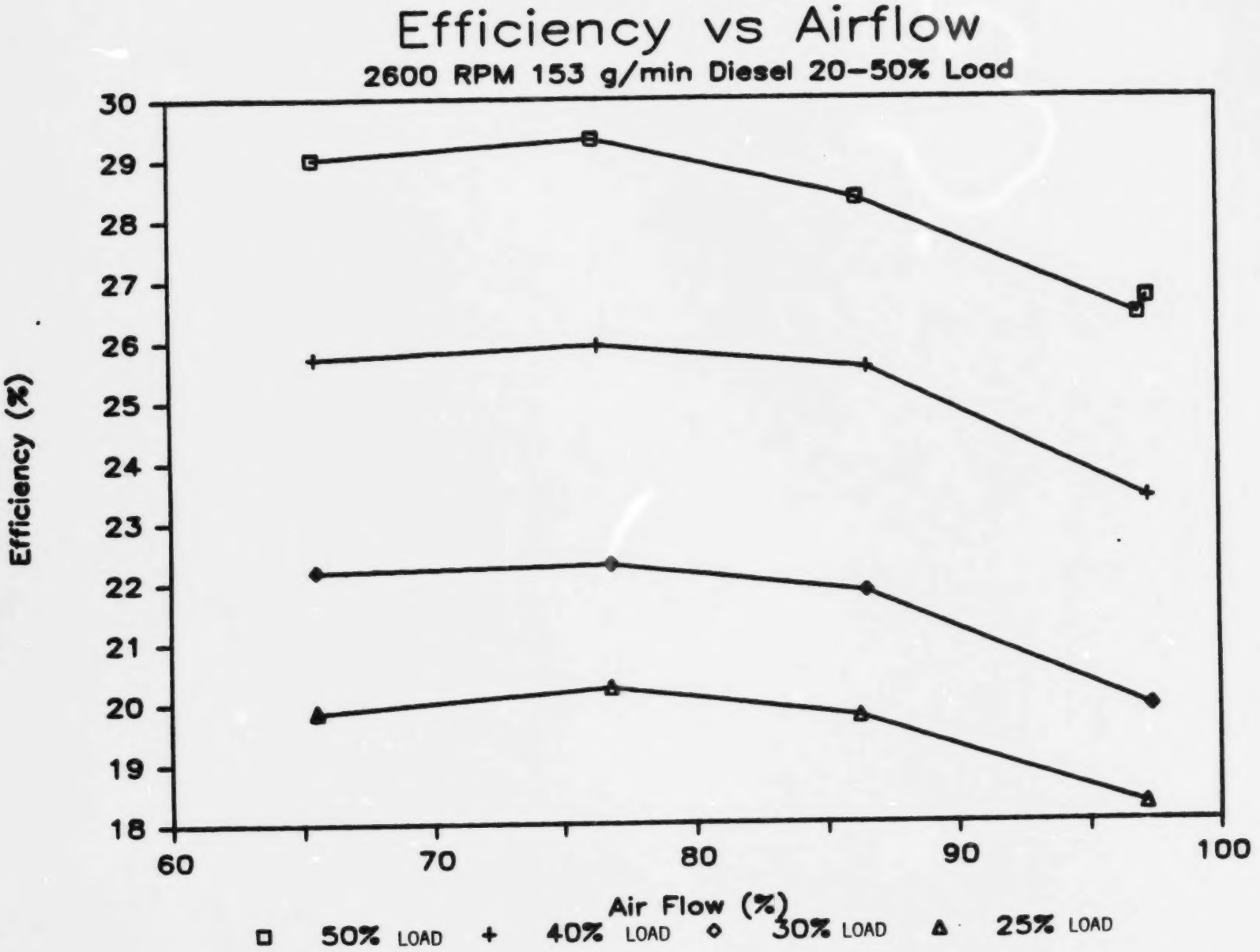

Efficiency vs Airflow
2600 RPM 153 g/min Diesel 20–50% Load
Efficiency (%)
30
29
28
27
26
25
24
23
22
21
20
19
18
60
70
80
90
100
Air Flow (%)
50% LOAD
40% LOAD
30% LOAD
25% LOAD

FIGURE 4

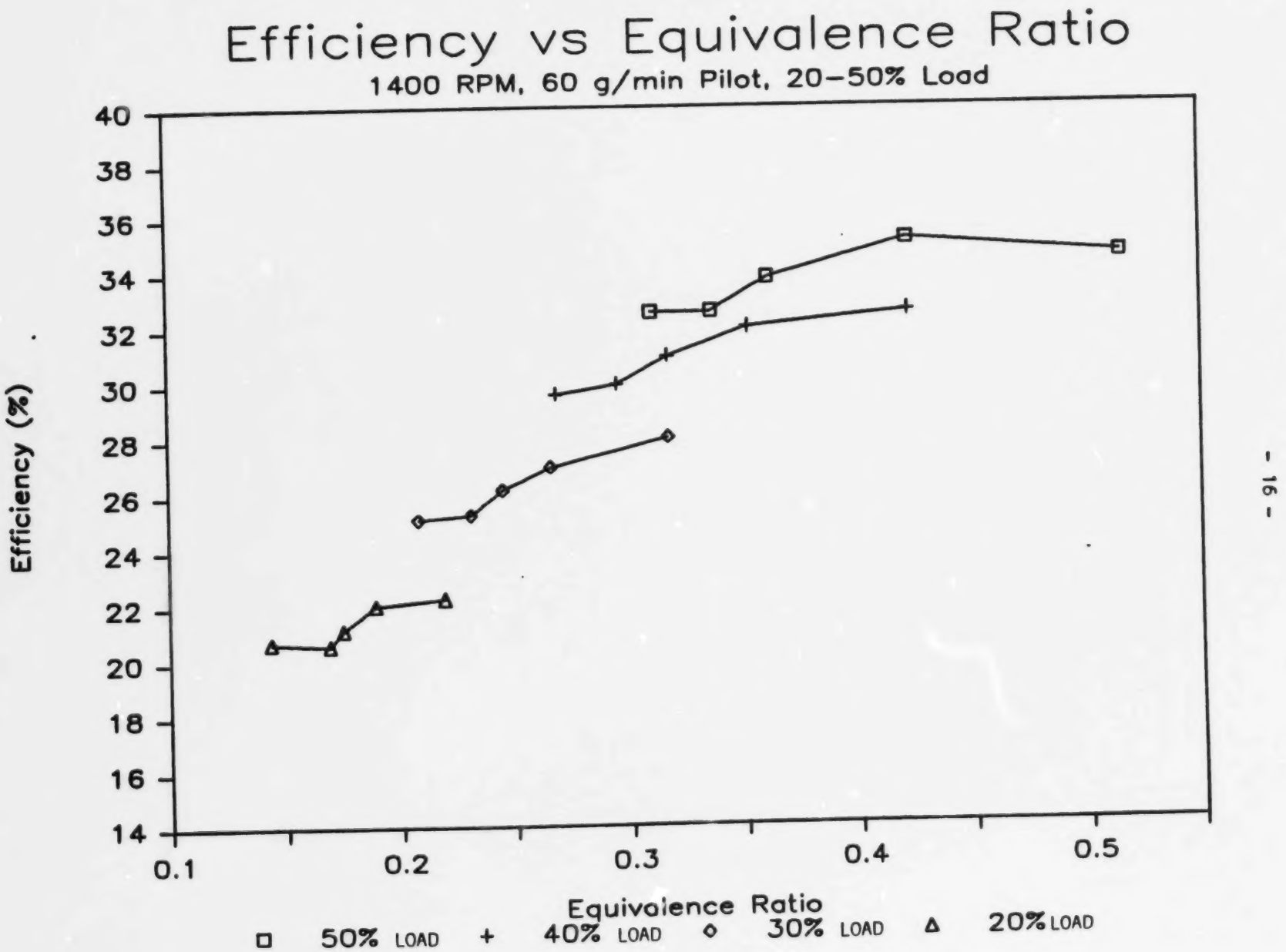

Efficiency vs Equivalence Ratio
1400 RPM, 60 g/min Pilot, 20–50% Load
Efficiency (%)
40
38
36
34
32
30
28
26
24
22
20
18
16
14
0.1
0.2
0.3
0.4
0.5
Equivalence Ratio
□ 50% LOAD
+ 40% LOAD
◇ 30% LOAD
△ 20% LOAD

FIGURE 5

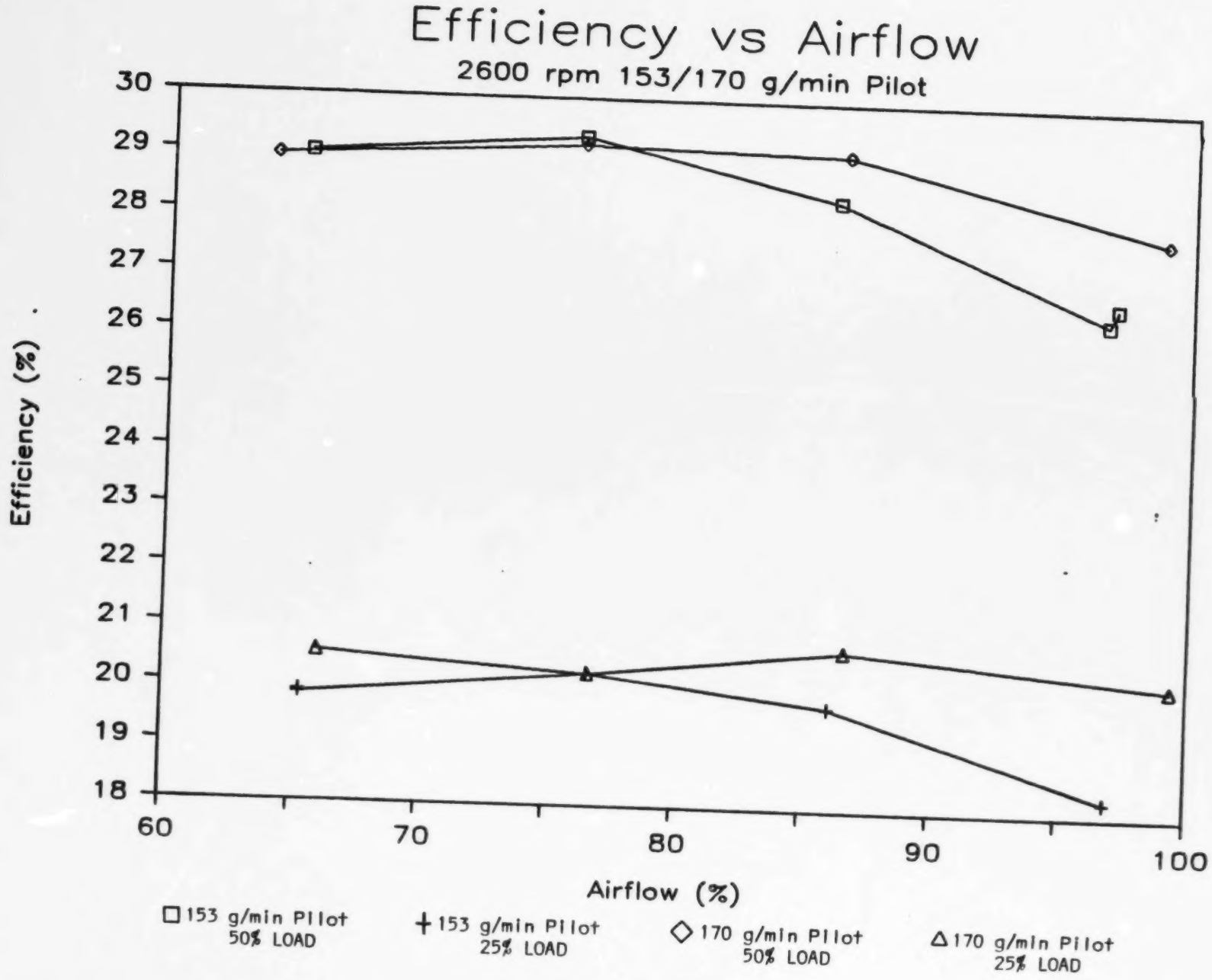

Efficiency vs Airflow
2600 rpm 153/170 g/min Pilot
Efficiency (%)
30
29
28
27
26
25
24
23
22
21
20
19
18
60
70
80
90
100
Airflow (%)
153 g/min Pilot 50% LOAD
153 g/min Pilot 25% LOAD
170 g/min Pilot 50% LOAD
170 g/min Pilot 25% LOAD

FIGURE 6

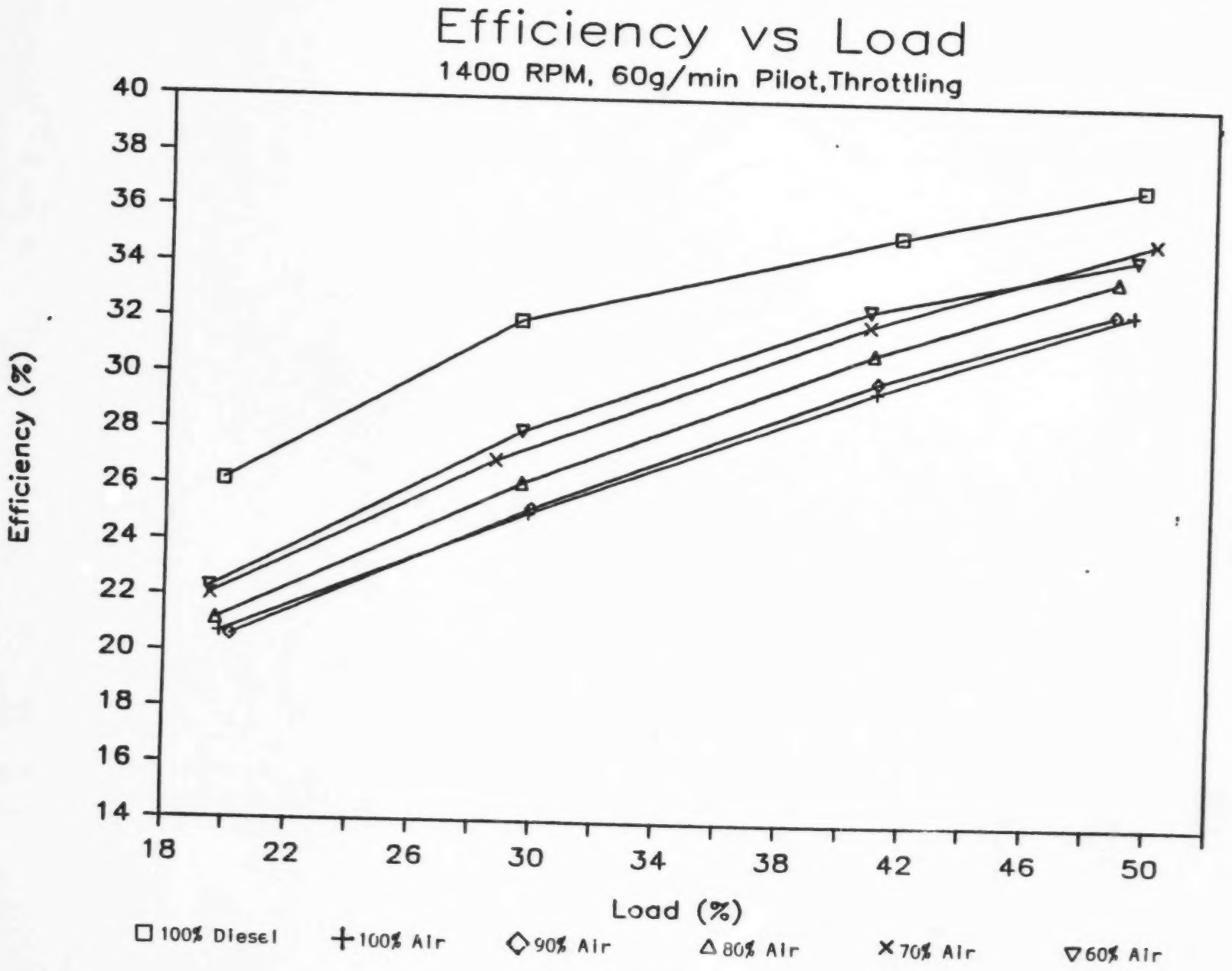

Efficiency vs Load
1400 RPM, 60g/min Pilot,Throttling
Efficiency (%)
40
38
36
34
32
30
28
26
24
22
20
18
16
14
18
22
26
30
34
38
42
46
50
Load (%)
100% Diesel
100% Air
90% Air
80% Air
70% Air
60% Air

FIGURE 7

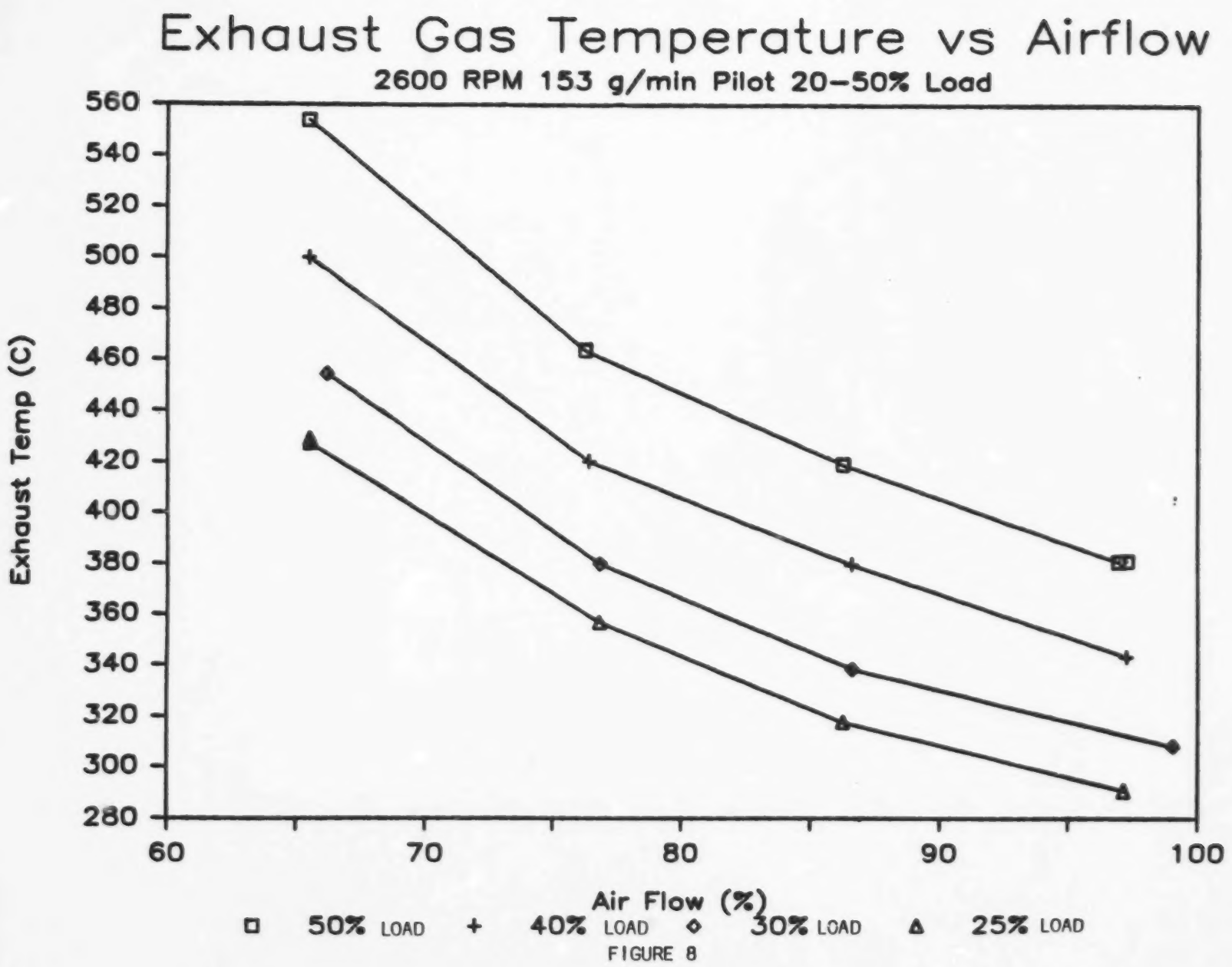

Exhaust Gas Temperature vs Airflow
2600 RPM 153 g/min Pilot 20-50% Load
Exhaust Temp (C)
560
540
520
500
480
460
440
420
400
380
360
340
320
300
280
60
70
80
90
100
Air Flow (%)
50% LOAD
40% LOAD
30% LOAD
25% LOAD

FIGURE 8

This work has been done on an experimental basis with no attention paid to any of the long term effects of operating at higher temperatures, and with components not designed to deal with sub-atmospheric pressures in the inlet tract. Throttling is not recommended at greater than half load due to increases in exhaust temperatures, and because the efficiency of the unthrottled dual fuel engine approaches that of the diesel engine.

4.2 Exhaust Gas Recirculation Tests

EGR tests were carried out at speeds of 1400 and 2600 rpm at two fuel flow rates. The results from the EGR tests showed that there was an increase in efficiency [Figure 9], but that the increase was not as great as by throttling. One reason for this was that our EGR test setup was too restrictive. We required an exhaust gas recirculation rate of 40% (to compare with throttling tests), and to give this flow rate, a throttle was required in the exhaust. To get 40% exhaust gas recirculation rate at 2600 rpm required 60 kPa pressure in the exhaust system, with an accompanying loss in efficiency. A second reason was the oxygen content of the exhaust. Diesel exhaust in the 20-50% load range will typically have an oxygen content of 14-17%, which gives a relatively lean mixture compared to the same amount of throttling. For example, an unthrottled air fuel mixture becomes 66% richer when throttled to 60% of original airflow. When EGR is used to reduce inlet air flow to 60%, the mixture becomes 25% richer. This is the same effect as throttling to 80% of the original airflow, as can be seen in Figure 10.

EGR had a stronger effect on efficiency when the engine was operating on the smaller amount of pilot fuel. This was comparable to the proportionally stronger effect during throttling and is also due to increasing the air fuel ratio. The effect on exhaust gas temperature is shown in Figure 11. The temperature increase is due to higher back pressure as well as the effect of the richer mixture. The effect of EGR on diesel fuel operation is shown in Figure 12. Note that there is a decrease in efficiency due to high back pressure. However for small amounts of back pressure and EGR there was a slight increase in efficiency. This is due in both cases to richening the overall mixture due to restrictions in the air inlet flow.

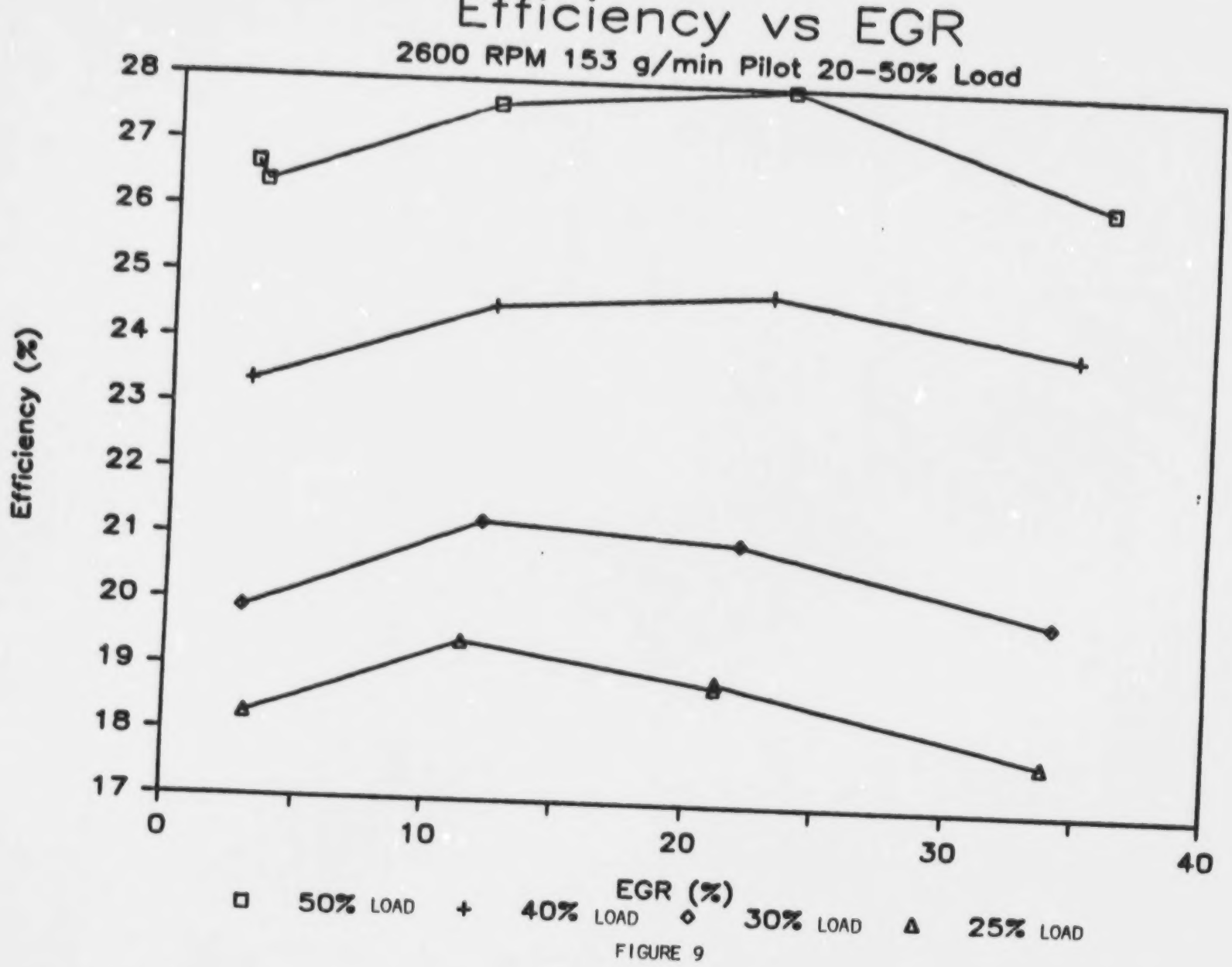

Efficiency vs EGR
2600 RPM 153 g/min Pilot 20–50% Load
Efficiency (%)
28
27
26
25
24
23
22
21
20
19
18
17
0
10
20
30
40
EGR (%)
50% LOAD
40% LOAD
30% LOAD
25% LOAD

FIGURE 9

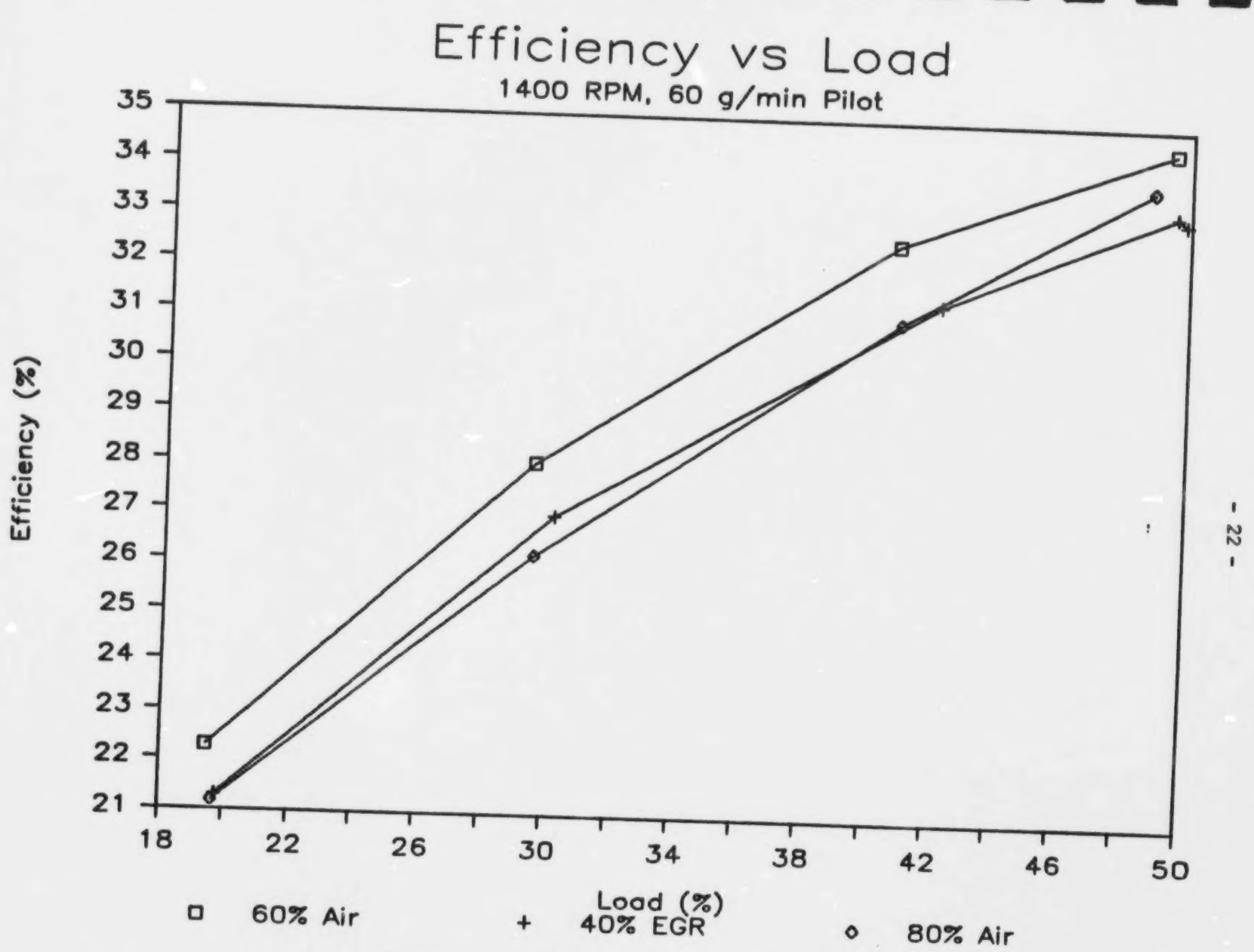


FIGURE 10 COMPARISON OF EGR AND THROTTLING

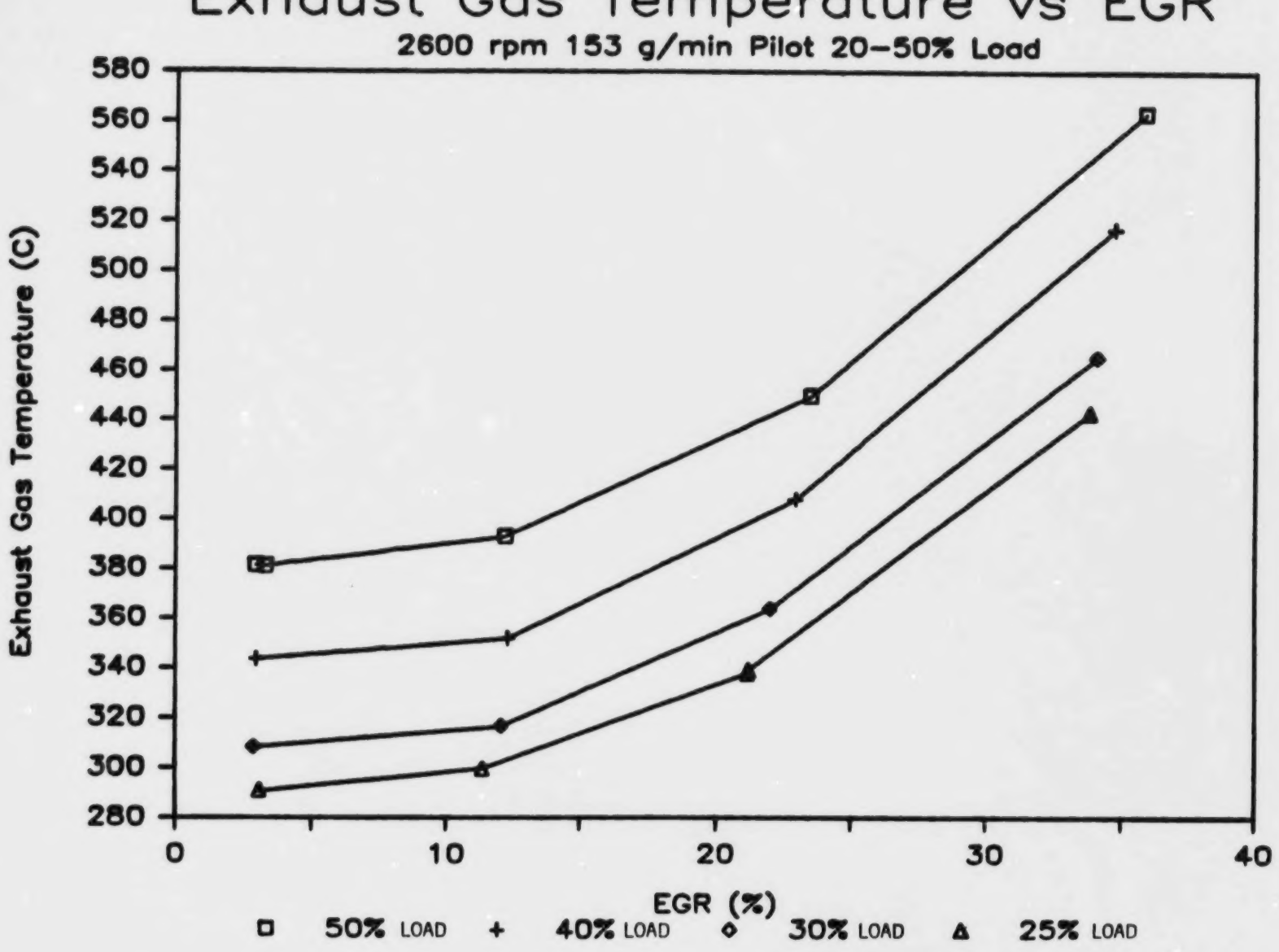

Exhaust Gas Temperature vs EGR
2600 rpm 153 g/min Pilot 20-50% Load
Exhaust Gas Temperature (C)
580
560
540
520
500
480
460
440
420
400
380
360
340
320
300
280
0
10
20
30
40
EGR (%)
50% LOAD
40% LOAD
30% LOAD
25% LOAD

FIGURE 11

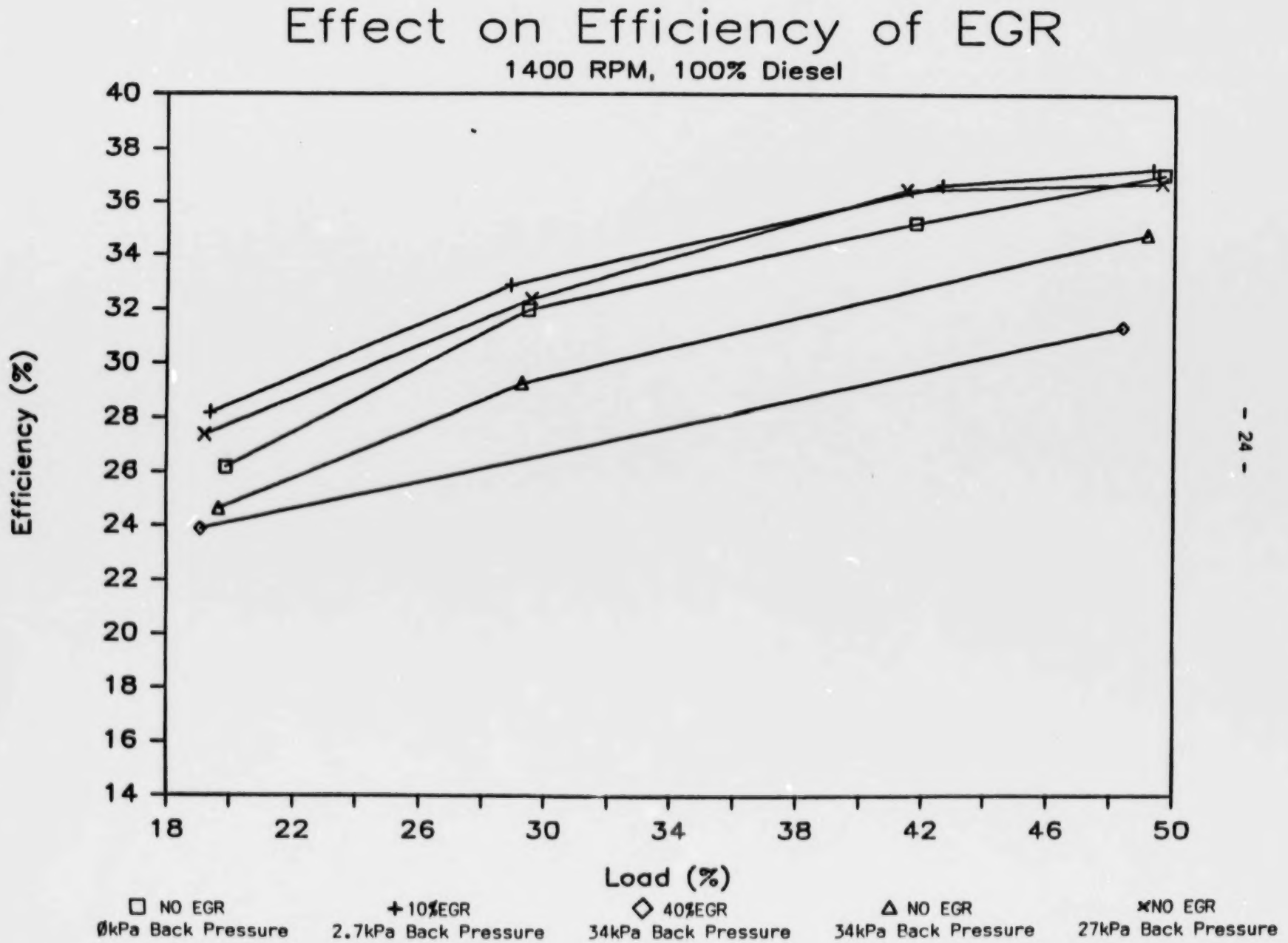

Effect on Efficiency of EGR
1400 RPM, 100% Diesel
Efficiency (%)
40
38
36
34
32
30
28
26
24
22
20
18
16
14
18
22
26
30
34
38
42
46
50
Load (%)
□ NO EGR
ØkPa Back Pressure
+ 10%EGR
2.7kPa Back Pressure
◇ 40%EGR
34kPa Back Pressure
△ NO EGR
34kPa Back Pressure
×NO EGR
27kPa Back Pressure

FIGURE 12

Exhaust gas recirculation has the following effects on light load efficiency:

- Increases efficiency, but not to the same extent as throttling for the same amount of intake air. This could be due to the oxygen content of the exhaust, thus causing the air fuel ratio to be leaner than it would be from throttling.

- Causes an increase in exhaust temperature. This is due to the richer air fuel ratio, increased intake temperature caused by mixing exhaust with intake air, and due to restriction in the exhaust system needed to provide sufficient gas flow.

Exhaust gas recirculation has the potential to increase efficiency at light load with dual fuel engines, but the system will require large diameter plumbing in order to provide the required flow with minimum restriction to the rest of the exhaust system. Further, large amounts of EGR will cause the fuel mixture to be too rich at heavy loads causing smoke and reduction of peak power. Finally, effects on the engine including inlet tract, combustion chamber, injectors, and turbochargers of large amounts of exhaust particles need to be investigated.

5.0 CONCLUSIONS

Both throttling and exhaust gas recirculation increase efficiency of dual fuel diesel engines at light load. In both cases, a smaller amount of pilot fuel can be used with comparable efficiency. Throttling seems to have a stronger effect on efficiency than EGR, but this effect may be due to throttling giving a richer mixture at a given intake airflow due to the presence of oxygen in the exhaust.

EGR and throttling both increase exhaust temperature. Effects on the engine of increased temperatures, reduced pressures in the inlet tract and cylinders (for throttling), the effects of exhaust particles in the inlet tract and cylinders, and additional exhaust back pressure (for EGR) require further investigation.

This work was carried out on a naturally aspirated engine. To extend this work to turbocharged engines will require changes to the experimental system. Turbochargers cannot be throttled without risk of running into surge, or unacceptable increases in inlet temperature. With EGR, it will be necessary to determine the effect of exhaust gas on the compressor, and determine ways to have optimal exhaust flow when required.

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